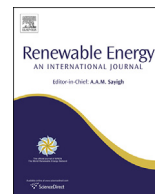




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Design considerations and performance evaluation of outdoor PV battery chargers

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ABSTRACT

Two main challenges are encountered in photovoltaic (PV) based battery chargers, namely, the variable input power and the fluctuating temperature. As a result, traditional charging techniques that rely only on the terminal measurements such as the current, voltage or temperature are not reliable in those chargers. Furthermore, relying only on the terminal measurements without other indirect measurements can result in terminating the charge before the battery is truly fully charged, which has several drawbacks such as reducing the usable capacity and possibly leading to memory effect in nickel-based batteries, or overcharging the battery which can lead the battery to prematurely reaching its end-of-service. This paper presents design considerations and evaluates the performance of PV chargers used to charge major battery chemistries including nickel–cadmium (NiCd), nickel–metal–hydride (NiMH), lithium-ion (Li-ion) and sealed lead-acid batteries at real operating conditions.

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1. Introduction

Renewable energy technologies have been gaining great attention recently due to environmental issues such as the continuously increasing levels of CO₂ emissions as well as strategic economic issues related to expected lack of fossil fuel. As a result, many countries around the globe have taken actions to increase the amount of power generated by renewable sources. As an example, in UAE, the average solar radiation year round has one of the highest values in the world [1]. In order to diversify the energy resources in UAE, which is among the highest priorities in the country, UAE has legislated many new policies recently to encourage the use of renewable energy sources such as solar power. Abu Dhabi's Economic Vision –2030 aims at generating 7% of Abu Dhabi energy requirements from renewable resources. In Dubai, it is projected to generate 1% of electricity needs from renewable sources by 2020 and 5% by 2030.

As a result of the intermittent nature of PV power, PV systems are usually backed up with batteries in order to minimize the fluctuations in the generated power. However, batteries are expensive and are the least reliable part of a renewable energy system. In addition, batteries usually reach their end-of-service life

prematurely adding more concerns to their reliability and feasibility. The battery quality gets even worse when exposed to high outdoor temperatures like in UAE. Table 1 lists some climate data for the UAE.

According to [3], battery charging is the most critical function of a battery management system. Basically, a battery charger must deliver the charge to the battery, optimize the charge rate, and terminate the charge when the battery gets fully charged. PV chargers are advantageous in the sense that they don't need to be plugged into an electricity outlet since they are powered directly from the sunlight. They can be ideally used during outdoor events to charge portable electronics, renewable backup batteries or even plugin electric vehicles provided enough sunlight is available. However, since the solar power and outdoor temperature are uncontrollable, traditional charging techniques fail to charge the battery reliably and safely. In addition, terminating the charge on time is a challenging task in those chargers due to the continuously varying charging power and ambient temperature. Therefore, terminating the charge in outdoor PV chargers must not rely only on the terminal (direct) measurements as in traditional chargers, but also on indirect measurements.

In this paper, design considerations for outdoor PV battery chargers are presented. The main goal of this study is to attain a solid understanding of all design requirements and challenges in outdoor PV chargers for the stand-alone PV system at the Renewable Energy Laboratory at UAE University. This 5 kW PV system backed up with 48 kWh lead-acid battery bank will be extended to

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Table 1
Climate data for UAE [1,2].

	Jan.	Feb.	March	April	May	June
MSR	7410	8670	7710	8410	9760	9820
ASH	8.1	8.6	8.7	10.2	11.3	11.5
MAXT	23.9	25.4	28.4	33.0	37.7	39.5
MANT	14.3	15.5	17.7	21.0	25.1	27.3
	July	Aug.	Sep.	Oct.	Nov.	Dec.
MSR	9160	9150	8880	8500	7720	7010
ASH	10.7	10.5	10.3	9.9	9.3	8.2
MAXT	40.9	41.3	38.9	35.4	30.6	26.2
MANT	30.0	30.4	27.7	24.1	20.1	16.3

MSR: Monthly solar radiation in kWh/m² per day.

ASH: Average sunshine hours per day.

MAXT: Monthly average maximum temperature in degree Celsius.

MANT: Monthly average minimum temperature in degree Celsius.

include more PV panels and energy storage units to partially cover the electricity demand of the campus. The Renewable Energy Laboratory at UAE University campus is shown in Fig. 1.

The organization of this paper is as follows: Section 2 reviews some design related issue for the power conversion stage. Section 3 presents some traditional charging techniques and evaluates those techniques in outdoor PV chargers. Section 4 describes some ways to estimate the state-of-charge (SOC) of a battery to improve the charging process. The effect of the ambient temperature on the charging process is presented in Section 5. Summary and conclusions are given in Section 6.

2. Power conversion stage

The PV output power varies with sun irradiance and ambient temperature. Hence, DC–DC converter is added to regulate the output voltage and to control the PV system operating point around the maximum power point (MPP). Fig. 2 shows a simplified PV battery charging system.

To optimize the design of the power conversion stage, many aspects must be considered. These aspects are application dependent. One main aspect that must be addressed in any PV system in general is the grounding requirement. Ungrounded PV systems provide the best fire hazard reduction, where grounded PV systems provide the best personnel protection from electrical shock, according to [4]. Generally, for systems with relatively high voltages, grounding is substantial for safety, electromagnetic coupling suppression, and electromagnetic pulse protection (EMP) [5]. In the U.S., all electrical systems with voltages greater than 50 V must be grounded [6]. Grounding is achieved by either connecting the PV source itself to the ground and monitoring for ground faults, or by connecting all components including the PV source, power converter and metallic chassis to the ground.



Fig. 1. Stand-alone 5.5 kW PV system at UAE university.

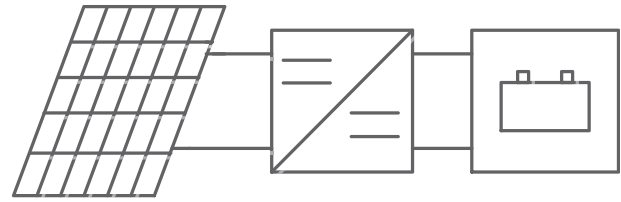


Fig. 2. A simplified block diagram of the PV charging system.

Another important issue is the galvanic isolation in the DC conversion stage. Transformers are commonly used in power converters since they provide galvanic isolation for safety reasons. According to the operating frequency of the transformer, the transformer can be a line-frequency (LF) or high frequency (HF) transformer. In general, LF transformers suffer from large volume and weight, high cost, low efficiency and low power factor especially under light load conditions. HF transformers, on the other hand, have a reduced weight, volume, and increased efficiency compared to LF transformers. For both LF and HF transformers, the efficiency of the whole system is decreased due to the losses in the transformer windings and core. Besides providing galvanic isolation, the transformer also provides voltage amplification, which is needed to boost the voltage of the DC input source when it is low. Occasionally, non-isolated (transformerless) converters are preferred due to their light weight, small volume and low cost as well as their high efficiency (1–2% efficiency improvement compared to HF isolated inverters) [7].

Also, it is important to optimize the number of conversion stages in a power converter to optimize the performance, efficiency, and cost. According to [5], single-stage converters offer simple structure and low cost, but suffer from a limited range of input voltage variations and are often characterized by compromised system performance because PV modules are connected in series to reach a high DC voltage at the input of the converter. On the other hand, multiple-stage converters operate over a wide range of input voltage variations, but suffer from high cost, complicated structure and lower efficiencies.

Additionally, the DC–DC converter must track the maximum power point by varying the operating voltage of the PV module, in real-time, in order to maximize the amount of power captured by the PV cells. A maximum power point tracking (MPPT) algorithm is usually integrated in a microprocessor chip. Different techniques are used to track the maximum power point. For example, heuristic search based techniques such as hill climbing and perturb and observe (P&O) algorithms are simple and easy-to-implement and are commonly used in PV MPPT chargers. However, those techniques result in continuous oscillation in the operating voltage which can reduce the amount of captured power. More advanced techniques include those that are based on fuzzy logic and artificial intelligence. Although those techniques have a very high performance, they are sophisticated and require advanced hardware for implementation. Other techniques such as extreme value searching, linear approximation methods, linear control techniques, array reconfiguration, linear current, and sliding control have their advantages and drawbacks [8].

A detailed block diagram of the PV subsystem at UAE University Renewable Energy Laboratory is shown in Fig. 3. This subsystem consists of 24 panels in three independent sets; each independent set consists of eight panels which are connected in two parallel strings with 4 in series in each string. Each panel has a maximum output power of 220 W with an open-circuit voltage of 36 V and short-circuit current of 8A. The DC–DC MPPT is connected in front of each set regulating the voltage to 48 V bus. Twenty (12 V, 200 Ah)

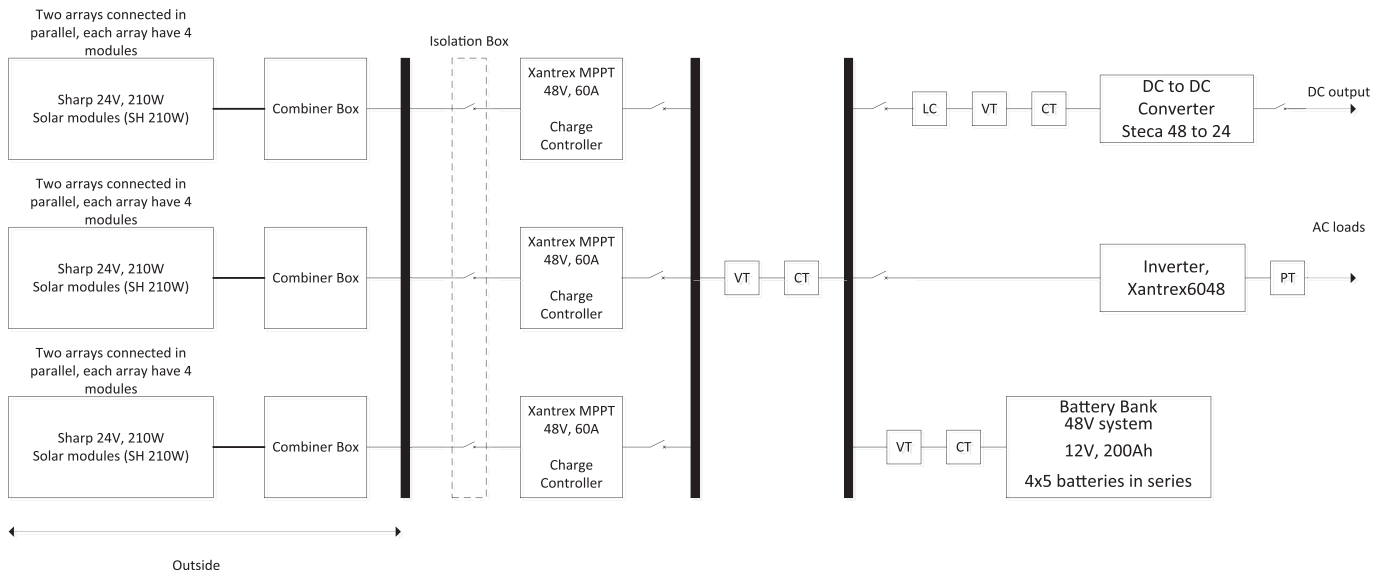


Fig. 3. A detailed block diagram of the PV system at UAE University Renewable Energy Laboratory. CB: circuit breaker; CC: current controller; CT: current sensing transformer; VT: voltage sensing transformer; LC: load controller.

batteries are connected in 5 parallel set with four in series at the DC bus. The current and voltage sensing transformers are used for fault diagnostic, monitoring, and energy management. Also, irradiance, wind speed, temp sensors are available on-site to monitor the weather conditions in real-time.

3. Charging techniques

Several techniques, ranging from basic to sophisticated, have been used to charge batteries. Some traditional and untraditional charging techniques are reviewed in this section. Since lead-acid batteries are the most common technology used in PV systems, their charging techniques are extensively reviewed.

3.1. Traditional techniques

The conventional charging method of constant current constant voltage (CCCV) has been evaluated on lead-acid batteries in Refs. [9–11]. This technique is divided into two stages, the first stage starts with constant current charging until a predefined voltage is reached, and then a constant voltage mode until a predefined current is reached. In Ref. [10], a comparison between different approaches of charging is presented. It was found out that using low constant current chargers is very economical due to the low implementation cost but does not optimize the battery performance. However, constant current chargers may lead to over-charging as they totally depend on the user to control the charging process. In Ref. [11], a study is conducted to compare between CCCV and multiple constant current constant voltage charging (MCC-CV) methods. It is shown that adding a negative pulse discharge to eliminate the polarization effect improves CCCV charging approach. According to [11], the charge capacity can be increased by increasing the current in the CC mode. However, to avoid polarization, the charger must switch to CV mode once the upper voltage limit is reached. The results show that the MCC-CV method with a negative pulse discharge is more efficient than CCCV method.

In Ref. [12], a pulse current charging technique is proposed for charging lead-acid batteries. In this technique, a large amount of current is applied at periodic intervals with a defined frequencies and duty cycles to increase the charging efficiency. According to

[12], there is a minimum pulse width to charge the battery with; otherwise, the pulse energy will be consumed by the charge reaction. The study shows that the invariant pulse technique has more charge delivery over the two-step conventional charging, but it doesn't work well at high SOC. The study also shows that the variable pulse strategy improves the charge rate significantly and eliminates gassing at high SOC which is a drawback in the invariant pulse technique.

In Ref. [13], battery charging has been evaluated as function of pulse frequency, duty cycle and amplitude. 12 V/7 Ah lead-acid batteries were tested by varying the duty cycle and frequency of the pulse current to find an optimal combination that improves the charge efficiency and minimize the temperature rise.

Other work has been reported in which a pulse discharge current was inserted during the charging process to improve the overall charging process. For example, in Ref. [14], a scheme for fast charging with a negative pulse discharge was presented. This technique was proposed to improve negative effects of charging using constant current/limit voltage, and it claimed that adding a negative pulse discharge to the previous method can improve the charging process. In the same work, a constant current of 70A and a threshold voltage of 14.5 V were used. The duration of the negative pulse was 100 ms–600 ms. The amplitude of the negative pulse was taken as 85%–115% of the capacity of the battery in order to notice the depolarization effect and avoid battery damage. The suggested method has some advantages such as short charging time and low temperature rise.

As for other batteries such as nickel- and lithium-based batteries, different charging techniques are commonly used [15–20]. For NiCd and NiMH batteries, a constant current is widely used to charge the battery until it becomes fully charged. When it is fully charged, either a voltage drop or a sudden rise in the temperature is considered an indication of a full charge status at which the charge must be terminated to avoid battery damage. For NiCd, the voltage drop is more obvious than in NiMH. Usually, the charge is terminated in NiCd batteries when a voltage drop of 8–12 mV/cell is detected, while it is around 3 mV/cell in NiMH batteries. Also, the charge is terminated in NiMH batteries when a sudden increase in the temperature is detected, which is another indication that the battery is fully charged. Sometimes the charging of a NiCd or NiMH

battery is terminated if either a voltage drop or a rise in temperature is detected. As for nickel batteries, partially charging those batteries have severe impact on the battery performance especially NiCd batteries due to memory effect, which is a term used to describe the degradation in the battery capacity when it is partly charged and discharged. Therefore, nickel battery chargers must avoid terminating charging before the battery is truly fully charged. Li-ion and lead-acid batteries are often charged through two charging stages: constant current and constant voltage. In the first stage, a constant current is applied to the battery until a predefined voltage is reached. After that, a constant voltage is applied across the battery until the current drops to 5–10% of its original value. However, for Li-ion and lead-acid, there are no indications such as voltage drop or temperature rise that can be used as indicators of full charge status. Therefore, a voltage limit is usually set before charging.

It is not uncommon, however, to use more than one technique to terminate the charging process to prevent the battery of getting overcharged. For example, in Ref. [21], a traditional charging algorithm is used to charge NiCd/NiMH batteries. A constant current is used during charging until an inflection point is detected. Once an inflection point (the point on the voltage curve at which the first derivative is zero) is detected, the charger switches to trickle charging to prevent overcharging the battery. Other charge termination techniques are implemented in this algorithm such as voltage drop, temperature rise and timing, in order to improve the charger performance.

Other techniques are claimed to optimize the charging efficiency and cycle-life of the battery such as pulse charging (PC), sinusoidal ripple charging (SRC), trickle charging, float charging and interrupted charge control (ICC) [21–35].

3.2. Untraditional techniques

Although traditional charging techniques can still be used in PV chargers, other supportive techniques must be implemented to ensure a reliable and safe charging process. For example, an algorithm is proposed in Ref. [36] for solar NiCd/NiMH battery chargers. The algorithm tracks the maximum battery voltage continuously and calculates the derivative of the voltage and the variation in the current in a sliding window of 5–10 min. The maximum voltage and the voltage drop will reset if at least the variation in the current or the derivative of the voltage exceeds some predefined threshold values. Otherwise, the charging continues until a significant voltage rise followed by a voltage drop above a certain threshold occurs.

In the same work in Ref. [36], another algorithm is proposed. The concept of this algorithm is to divide the battery into two legs inside the battery pack and monitor the temperature of each leg individually. Ideally, the difference in temperature between the two legs must be negligible during charging regardless whether the ambient temperature changed or not. If a high positive temperature derivative is detected in one of the legs, the charger will keep charging this leg while it stops charging the other one. After a certain time, if the temperature derivative reaches a predefined value, the algorithm will detect overcharge in that leg.

In Ref. [37], a solar battery charger algorithm is proposed to charge different batteries. The battery is charged with current pulses at a duty cycle of 50% to increase the accuracy of the voltage measurement at the end of each rest cycle. As reported, the charger speed can be improved when two batteries are charged simultaneously since all the solar power is utilized to charge each battery in its charge cycle. The charger charges the battery with the current obtained from the solar array for 3 min (charge cycle) and disconnects the battery for another 3 min (rest cycle). The voltage at the end of each rest cycle is monitored and compared with the

previous value. If the voltage increases, the algorithm checks if the voltage is within a predefined Li-ion range. If the voltage is not in one of the predefined ranges, charging will continue. The voltage drop is also monitored at the end of each rest cycle. If a voltage drop greater than a threshold value is detected, charging will be terminated and the battery will be either a NiCd or a NiMH battery. If no voltage drop was detected and the battery voltage at the end of a rest cycle was in the safety limit range of Li-ion battery, CV mode will start and the current will be monitored until it drops below a threshold value at which charging will be terminated and the battery will be Li-ion.

Fig. 4 illustrates traditional pulsed-current charging technique (20A, 50 Hz, 50% duty cycle) used to charge a gel lead-acid battery. Fig. 5 illustrates the modified pulse charging (ICC technique) performed on two nickel batteries (NiCd and NiMH).

3.3. Evaluation

Traditional charging techniques vary in terms of their effectiveness, complexity and ease of implementation. Those techniques that use constant current (CC) or CCCV strategy represent the simplest among the reviewed methods. However, CC and CCCV charging methods usually fail to optimize the charging rate and they overcharge the battery, which will eventually result in reduced battery cycle-life [38]. The pulse-current charging techniques include a rest period that allows the electrolyte's ions to distribute more evenly; thus, compared to CC and CCCV methods, pulsating techniques are more effective in the sense that they offer a higher charging efficiency which can improve the battery's cycle-life, but their implementation cost is more expensive. The pulse charging techniques with short negative pulses are claimed to speed up the diffusion effect and the electrolyte density neutralization; however, the effectiveness of those techniques on the charging efficiency and battery's cycle-life must be further researched on different battery types before they are implemented. Untraditional techniques, on the other hand, are somehow similar to traditional techniques except that they employ different charge termination strategies.

All the presented techniques (traditional and untraditional) solely rely on the external behavior of the battery. That is, the charge operation is totally controlled based on the sensed voltage and temperature. However, the battery's voltage is a function of charging current, SOC and temperature. In addition, the temperature rise in the battery can be a result of internal heat or due to ambient temperature rise. Hence, relying only on the battery terminal measurements, the charging operation cannot be optimized and the battery lifetime as well as the safety will be real concerns unless advanced techniques are used to estimate the amount of energy in the battery at any condition is implemented alongside with the charging algorithm.

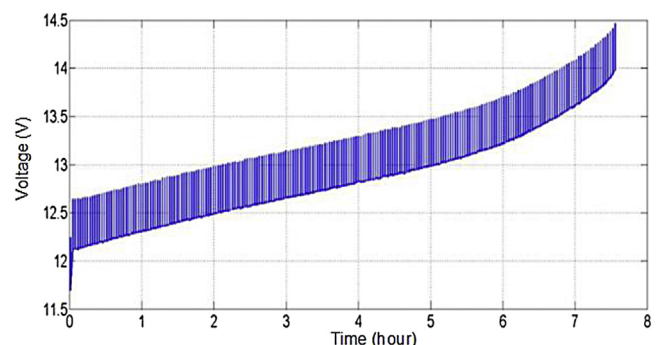


Fig. 4. Pulse charging (20A, 50 Hz, 50% duty cycle) for a 12 V gel lead-acid battery.

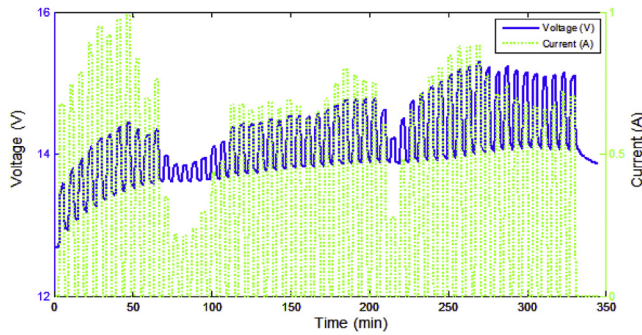


Fig. 5. ICC charging in Ref. [12] for 12 V NiCd and NiMH batteries.

4. SOC tracking

In order to terminate the charge only when the battery gets fully charged, which is very tricky in PV chargers, an important parameter must be continuously tracked. This parameter is the SOC, which is defined as an indication of the amount of energy inside the battery compared to its maximum capacity. The SOC is mathematically expressed in (1).

$$\text{SOC}(t) = \text{SOC}(0) + \eta \int_0^t \frac{i(\tau)}{C_T} d\tau \quad (1)$$

In discrete-time domain, equation (1) can be rewritten as in (2)

$$\text{SOC}_k = \text{SOC}_{k-1} + \eta \frac{i_k \Delta t}{C_T} \quad (2)$$

where $i(t)$ is the current as a function of time (positive for charging and negative for discharging), i_k is the current at instance k , C_T is the total capacity (in Ah), and η is the (dis)charge efficiency, which can be obtained from the manufacturer datasheet or found experimentally as given in equation (3), where $C_{(\text{dis})\text{ch}}$ is the (dis)charge capacity (in Ah).

$$\eta = \frac{C_{(\text{dis})\text{ch}}}{C_T} \quad (3)$$

For a reliable charger design, the charge must be terminated only once the SOC is 100%. Therefore, an accurate and reliable mechanism for SOC estimation is substantial. In fact, the methods used in inexpensive chargers such as negative voltage drop or temperature rise in nickel batteries overcharge the battery [39], and reduce its cycle-life. Therefore, estimating the SOC continuously can significantly improve the charging process.

Many SOC estimation techniques have been used in different applications [39]. Among those techniques, coulomb-counting or current integration is a well-known technique that is used in many commercial applications to estimate the battery SOC. It has several advantages such as it can be used in real time and is very accurate if accurate current measurements are provided. However, one limitation of this technique is that it can't estimate the initial SOC. In other words, there is no way to predict the true SOC if the initial SOC is unknown. To overcome this limitation, the open-circuit voltage (OCV) technique can be used to estimate the initial SOC by employing an OCV-SOC lookup table. Before starting the charging process, the terminal voltage of the battery is measured and the corresponding initial SOC to the measure voltage is found from the lookup table. Then, the accumulated charge is calculated and the SOC is continuously updated as described in equation (1).

Once a 100% SOC is reached, the charging process will be terminated.

To estimate the initial SOC, an OCV-SOC lookup table for a 1100 mAh Li-ion battery cell was created at room temperature as in Table 2, which represents a portion of an extended table. In Table 2, the OCV was found experimentally by charging and discharging the battery cell at very low current rates, and then averaging the charge and discharge voltages and pairing the averaged voltages with their corresponding SOC. However, linear interpolation is used whenever the measured OCV lies outside the lookup table. Fig. 6 shows a solar current profile. The current rise in Fig. 6 represents a sudden increase in the solar radiation, while a drop in the current is equivalent to a sudden decrease in the radiation. Fig. 7 shows four charging tests with different initial SOC (15%, 30%, 50% and 80%). The initial SOC was determined from the OCV-SOC lookup table. The charge was only terminated once the SOC reached 100% although the different initial SOC values used in the tests.

In Fig. 6, the sudden change in the current will cause a sudden change in the terminal voltage of the battery. Inexpensive chargers that rely only on the terminal measurements will terminate the charging process once a sudden change in the voltage is detected. However, with an SOC tracking algorithm, the charging process will go on and will stop only when the battery is truly fully charged as shown in Fig. 7.

5. Ambient temperature

The performance of any battery is greatly impacted by the ambient temperature at which the battery operates, which is a major limiting factor in PV chargers. This temperature-dependence behavior is a result of the variation in the physical properties of the inner components of the battery cell. Basically, a cell consists of two electrodes (negative anode and positive cathode), electrolyte, and a porous separator to isolate the two electrodes [10]. The transport, kinetic, and mass-transfer properties of these components such as the thickness, density, specific heat, thermal conductivity, particle radius, and diffusion coefficient vary significantly with temperature [40]. This temperature dependence of the cell results in variation in the total capacity of the battery, which results in inaccurate SOC estimation if not addressed well according to equation (1). To address this temperature-dependence of the cell in the PV charger, advanced charge termination techniques must be implemented. As the temperature increases, the chemical reactions inside the cell are stimulated resulting in a higher speed of reactions and increased capability of holding energy though high temperatures increase the oxidation in the cell and decreases the cell's expected lifetime due to active materials breakdown.

To examine the effect of temperature on the battery, a 1100 mAh Li-ion battery cell was fully charged then completely discharged at different temperatures and its discharged capacity at each temperature was recorded as shown in Fig. 8. It was found that at 50 °C, the capacity increases by 2.8% while at 0 °C it decreases by 4.8% of the room temperature capacity (at 23 °C). In order to improve the accuracy of the SOC estimation of the charger, the values of the capacity at different temperatures must be stored in a lookup table

Table 2
OCV-SOC lookup table.

Initial OCV	Corresponding SOC
2.200	0%
3.226	15%
3.284	30%
3.309	50%
3.345	80%

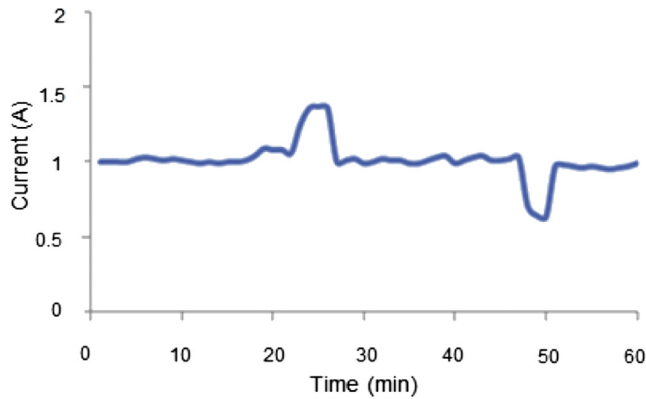


Fig. 6. Simulated solar current profile.

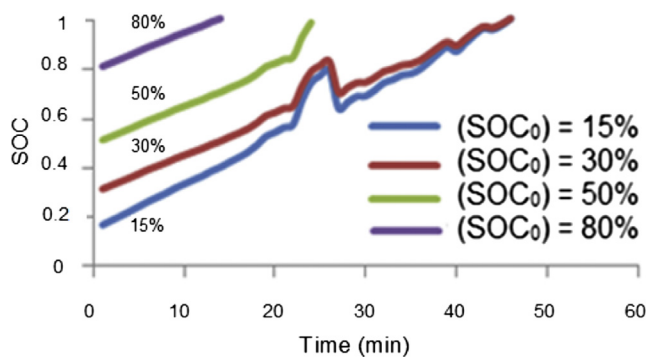


Fig. 7. SOC versus time with 15%, 30%, 50% and 80% initial SOC.

and used to estimate the SOC at any temperature in order avoid unreliable runtime prediction due to inaccurate SOC estimations according to (1).

As for the cell OCV, it was found that the OCV is also correlated with temperature. In order to improve the accuracy if the OCV-SOC lookup table at any temperature, different OCV-SOC lookup tables at different temperatures must be used. Fig. 9 shows the OCV-SOC curves obtained at different temperatures [41]. To establish a general relationship between the OCV and SOC at a wide range of temperatures, the following procedure was followed:

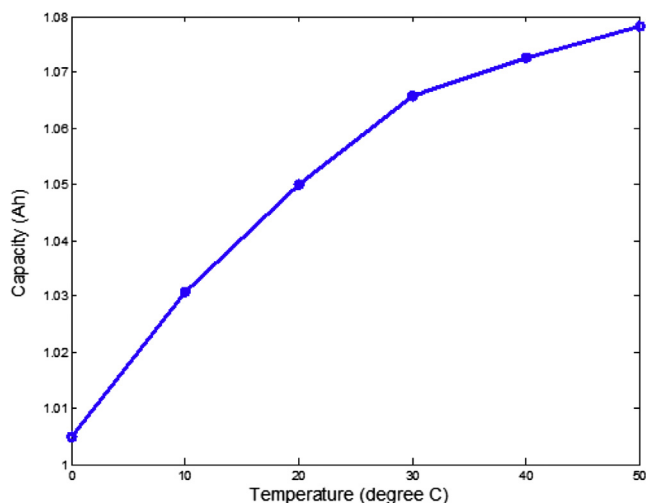


Fig. 8. Capacity versus temperature for a 1100 mAh Li-ion battery cell.

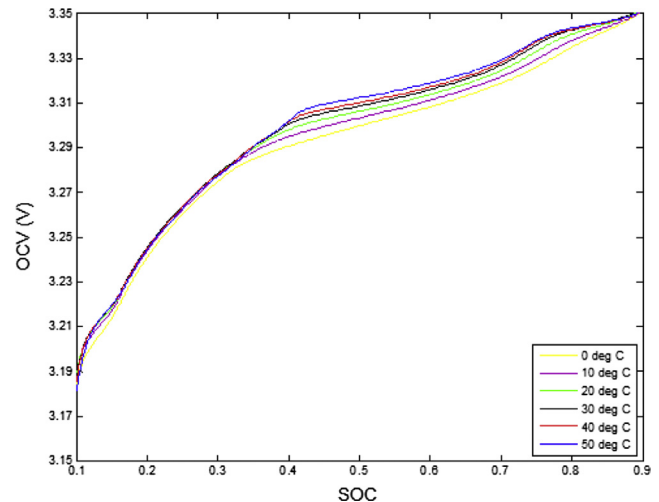


Fig. 9. The OCV-SOC curves at different temperature.

1. The cell is placed in the chamber and soaked at the test temperature for 4 h.
2. The cell is charged (constant current to 3.6 V then constant voltage to 1 mA).
3. The cell is discharged at C/20 rate (55 mA) until the voltage drops to 2 V.
4. The cell is relaxed for few minutes.
5. The cell is charged at C/20 rate (55 mA) until the voltage reaches 3.6 V.

This procedure is repeated at each test temperature. The way the SOC and OCV values were calculated is similar to the calculations made at room temperature. The only difference is that the nominal capacity, which was found to be strongly dependent on temperature, was found first at each test temperature then used to find the OCV-SOC pairs at each temperature. The OCV versus SOC curves at these temperatures are shown in Fig. 9.

The variation in temperature has two-fold impact on the charging process. Firstly, it affects the SOC computation accuracy, according to (1), since the capacity is a function of temperature. This temperature dependence can be addressed by using different capacities at different temperatures. To do so, the capacity must be measured experimentally at all possible operating temperatures using an environmental chamber. Secondly, the variation in temperature reduces the reliability of those chargers that are programmed to terminate the charge when a sudden temperature rise is detected. The reason for prematurely terminating the charge in those chargers is that the rise in the cell's temperature can be a result of a sudden rise in the ambient temperature, which will be interpreted as a full charge statement and consequently the charger will terminate the charging process. One way to address this limitation is by computing the temperature derivative [36], or tracking the SOC of the battery.

6. Summary and conclusions

The design of an optimal PV battery charger poses many challenges. Since the charging power and outdoor temperature can vary significantly with the geographical location, season, and daytime, traditional charging techniques fail to terminate charging when the battery truly gets fully charged. Therefore, other techniques that not only rely on the terminal measurements, but also on the battery inner parameters must be implemented in order to improve the charging process and the lifetime of the battery.

In order to cope with the outdoor conditions especially at harsh environments, all design requirements for the PV battery charger must be carefully addressed. In this paper, it was stated that the hardware is optimized by addressing all the power stage design requirements such as: 1) grounding for high voltage systems; 2) transformer insertion for galvanic isolation and voltage amplification; 3) number of conversion stages to boost the input voltage to the desired value; and 4) MPPT algorithm in order to increase the utilization of the sunlight. In addition, recent charging algorithms for NiCd, NiMH, Li-ion and lead-acid batteries were presented and evaluated. Traditional charging techniques are unreliable for use in PV chargers due to the fact that traditional techniques solely rely on the terminal measurements. For a reliable PV battery charging algorithm, an estimation mechanism for the battery SOC must be used at all outdoor conditions. A modified coulomb counting technique with an OCV-SOC lookup table was developed and verified in this paper and showed satisfactory results. In addition, the charging algorithm must be more advanced compared to traditional charging algorithms. It was shown that the capacity as well as the relationship between the OCV and SOC can considerably change at different temperatures. In order to improve the accuracy of the SOC estimation mechanism, which is substantial in terminating the charge reliably in PV chargers, the temperature dependence must be incorporated in the capacity and OCV-SOC lookup tables.

In a country such as the UAE where temperatures can go to very high levels, the temperature impact on the charger design and battery lifetime must be carefully addressed to meet all design requirements. Since the design requirements vary dramatically from an application to another, the design of a charger is totally driven by the application.

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